

CLAIMS

What is claimed is:

1. A code division, multiple access (CDMA) receiver, comprising a receiver input for coupling to signal outputs of N_{rx} receive antennas, the signal outputs being sampled at N_s samples per symbol or chip, a matched filter, and a whitening filter for coupling the receiver input to an input of the matched filter, said whitening filter comprising $N_s N_{rx}$ parallel whitening filters $w_{j,k}$, individual whitening filters $w_{j,k}$ receiving, during each symbol interval I , $N_s N_{rx}$ new signal samples via a signal connection matrix such that a first individual whitening filter receives one of the new samples, a second individual whitening filter receives the same new sample as the first individual whitening filter, and one additional new sample, and such that an n th individual whitening filter receives the same $n-1$ new samples as the first $n-1$ individual whitening filters, plus one additional new sample, said whitening filter comprising N_{rx} outputs for outputting filtered signal samples such that a filtered signal sample appearing in the N_{rx} outputs does not correlate with any other filtered signal sample appearing in N_{rx} outputs.
2. A CDMA receiver as in claim 1, further comprising a delay line comprised of a plurality of serially coupled delay line elements each having a delay of one symbol interval, said delay line having an input coupled to an output of said signal connection matrix and providing the $N_s N_{rx}$ parallel whitening filters $w_{j,k}$ with delayed versions of said signal samples.
3. A CDMA receiver as in claim 2, where for a symbol interval i and where $N_s N_{rx} = 4$, signal vectors output from the delay line elements are defined as:

$$\mathbf{r}(i-1) = \begin{pmatrix} r_{1,1}(i-1) \\ r_{1,2}(i-1) \\ r_{2,1}(i-1) \\ r_{2,2}(i-1) \end{pmatrix},$$

where in the term $r_{n,m}(i)$ the symbols n and m denote an antenna and a symbol sample index, respectively, where an the input signal vector for an arbitrary one of the individual whitening filters $\mathbf{w}_{n,m}$ is denoted by $\mathbf{r}_{n,m}$, the signal connection matrix results in input signal vectors:

$$\mathbf{r}_{1,1}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \end{pmatrix} ; \mathbf{r}_{1,2}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \\ r_{1,2}(i) \end{pmatrix} ; \mathbf{r}_{2,1}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \\ r_{1,2}(i) \\ r_{2,1}(i) \end{pmatrix} ; \mathbf{r}_{2,2}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ \mathbf{r}(i) \end{pmatrix}$$

at the inputs to the individual whitening filters $\mathbf{w}_{n,m}$.

4. A CDMA receiver as in claim 3, where in a direct form solution, taking one of the signal vectors the signal model is expressed as

$$\mathbf{r}_{n,m}(i) = \mathbf{G}\mathbf{b} + \mathbf{n} = \begin{pmatrix} \mathbf{H} \\ \mathbf{h}^T \end{pmatrix} \mathbf{b} + \mathbf{n},$$

where $(\cdot)^T$ denotes transposition, \mathbf{G} is a channel matrix, possibly including the effect of transmitter and receiver filters, \mathbf{b} is a symbol vector and \mathbf{n} a noise vector, and vector \mathbf{h}^T is the bottom row of \mathbf{G} , the corresponding individual whitening filter $\mathbf{w}_{n,m}$ output is

$$g_{n,m}(i) = \mathbf{w}_{n,m}^H(i) \mathbf{r}_{n,m}(i),$$

where $(\cdot)^H$ denotes conjugate transposition.

5. A CDMA receiver as in claim 4, where an individual whitening filter $\mathbf{w}_{n,m}$ is obtained by using linear minimum mean-square error (LMMSE) criterion as

$$\mathbf{w}_{n,m}(i) = \begin{pmatrix} -\alpha \mathbf{C}_{n,m}^{-1} \mathbf{H} \mathbf{h}^* \\ 1 \end{pmatrix} = \begin{pmatrix} -\mathbf{u}_{n,m} \\ 1 \end{pmatrix},$$

in which $(\cdot)^{-1}$ denotes matrix inversion and $(\cdot)^*$ complex conjugation, where symbol α is a real scaling factor, and the covariance matrix of $\mathbf{r}_{n,m}(i)$ is

$$\mathbf{C}_{n,m} = \text{Expectation}\{\tilde{\mathbf{r}}_{n,m}(i)\tilde{\mathbf{r}}_{n,m}^H(i)\},$$

where the tilde above vector $\mathbf{r}_{n,m}(i)$ denotes an operation where the bottom element of the original vector is excluded.

6. A CDMA receiver as in claim 5, where the unfixed part $\mathbf{u}_{n,m}$ of the whitening filter is made adaptive in accordance with:

$$\mathbf{u}_{n,m} \leftarrow \mathbf{u}_{n,m} + \mu\{g_{n,m}^*(i)\tilde{\mathbf{r}}_{n,m}(i)\},$$

where parameter μ is a step size factor.

7. A CDMA receiver as in claim 1, where said whitening filter is implemented using serially coupled lattice stages that form a lattice filter.

8. A method for operating a code division, multiple access (CDMA) receiver, comprising:

coupling a receiver input to signal outputs of N_{rx} receive antennas, the signal outputs being sampled at N_s samples per symbol,

whitening the signal outputs; and

filtering the whitened signal outputs with a matched filter, where

whitening uses a whitening filter comprising $N_s N_{rx}$ parallel whitening filters $\mathbf{w}_{j,k}$, individual whitening filters $\mathbf{w}_{j,k}$ receiving during each symbol interval i , $N_s N_{rx}$ new signal samples via a signal connection matrix such that a first individual whitening filter receives only one of the new samples, a second individual whitening filter receives the

same sample as the first individual whitening filter, and one additional sample, and such that an n th individual whitening filter receives the same $n-1$ samples as the first $n-1$ individual whitening filters, plus one of the remaining samples, and outputting from said whitening filter, over N_{rx} outputs, filtered signal samples such that a filtered signal sample appearing in the N_{rx} outputs does not correlate with any other filtered signal sample appearing in N_{rx} outputs.

9. A method as in claim 8, further comprising operating a delay line comprised of a plurality of serially coupled delay line elements each having a delay of one symbol interval, said delay line having an input coupled to an output of said signal connection matrix and providing the $N_s N_{rx}$ parallel whitening filters $\mathbf{w}_{j,k}$ with delayed versions of said signal samples.

10. A method as in claim 9, where for a symbol interval i and where $N_s N_{rx} = 4$, signal vectors output from the delay line elements are defined as:

$$\mathbf{r}(i-1) = \begin{pmatrix} r_{1,1}(i-1) \\ r_{1,2}(i-1) \\ r_{2,1}(i-1) \\ r_{2,2}(i-1) \end{pmatrix},$$

where in the term $r_{n,m}(i)$ the symbols n and m denote an antenna and a symbol sample index, respectively, where an the input signal vector for an arbitrary one of the individual whitening filters $\mathbf{w}_{n,m}$ is denoted by $\mathbf{r}_{n,m}$, the signal connection matrix results in input signal vectors:

$$\mathbf{r}_{1,1}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \end{pmatrix} ; \mathbf{r}_{1,2}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \\ r_{1,2}(i) \end{pmatrix} ; \mathbf{r}_{2,1}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ r_{1,1}(i) \\ r_{1,2}(i) \\ r_{2,1}(i) \end{pmatrix} ; \mathbf{r}_{2,2}(i) = \begin{pmatrix} \vdots \\ \mathbf{r}(i-2) \\ \mathbf{r}(i-1) \\ \mathbf{r}(i) \end{pmatrix}$$

at the inputs to the individual whitening filters $\mathbf{w}_{n,m}$.

11. A method as in claim 10, where in a direct form solution, taking one of the signal vectors the signal model is expressed as

$$\mathbf{r}_{n,m}(i) = \mathbf{G}\mathbf{b} + \mathbf{n} = \begin{pmatrix} \mathbf{H} \\ \mathbf{h}^T \end{pmatrix} \mathbf{b} + \mathbf{n},$$

where $(\cdot)^T$ denotes transposition, \mathbf{G} is a channel matrix, possibly including the effect of transmitter and receiver filters, \mathbf{b} is a symbol vector and \mathbf{n} a noise vector, and vector \mathbf{h}^T is the bottom row of \mathbf{G} , the corresponding individual whitening filter $\mathbf{w}_{n,m}$ output is

$$g_{n,m}(i) = \mathbf{w}_{n,m}^H(i) \mathbf{r}_{n,m}(i),$$

where $(\cdot)^H$ denotes conjugate transposition.

12. A method as in claim 11, where an individual whitening filter $\mathbf{w}_{n,m}$ is obtained by using linear minimum mean-square error (LMMSE) criterion as

$$\mathbf{w}_{n,m}(i) = \begin{pmatrix} -\alpha \mathbf{C}_{n,m}^{-1} \mathbf{H} \mathbf{h}^* \\ 1 \end{pmatrix} = \begin{pmatrix} -\mathbf{u}_{n,m} \\ 1 \end{pmatrix},$$

in which $(\cdot)^{-1}$ denotes matrix inversion and $(\cdot)^*$ complex conjugation, where symbol α is a real scaling factor, and the covariance matrix of $\mathbf{r}_{n,m}(i)$ is

$$\mathbf{C}_{n,m} = \text{Expectation} \left\{ \tilde{\mathbf{r}}_{n,m}(i) \tilde{\mathbf{r}}_{n,m}^H(i) \right\},$$

where the tilde above vector $\mathbf{r}_{n,m}(i)$ denotes an operation where the bottom element of the original vector is excluded.

13. A method as in claim 12, where the unfixed part $\mathbf{u}_{n,m}$ of the whitening filter is made adaptive in accordance with:

$$\mathbf{u}_{n,m} \leftarrow \mathbf{u}_{n,m} + \mu \{ \mathbf{g}_{n,m}^*(i) \tilde{\mathbf{r}}_{n,m}(i) \},$$

where parameter μ is a step size factor.

14. A method as in claim 7, where said whitening filter is implemented using serially coupled lattice stages that form a lattice filter.

15 A code division, multiple access (CDMA) mobile station, said mobile station comprising a receiver coupled to N_{rx} receive antennas and further comprising baseband circuitry for sampling signal outputs of said N_{rx} receive antennas at N_s samples per symbol or chip, said baseband circuitry further comprising a multi-antenna RAKE receiver and a whitening filter for coupling the sampled signals to inputs of said multi-antenna RAKE receiver, said whitening filter comprising $N_s N_{rx}$ parallel whitening filters $\mathbf{w}_{j,k}$, individual whitening filters $\mathbf{w}_{j,k}$ receiving, during each symbol interval I , $N_s N_{rx}$ new signal samples via a signal connection matrix such that a first individual whitening filter receives one of the new samples, a second individual whitening filter receives the same new sample as the first individual whitening filter, and one additional new sample, and such that an n th individual whitening filter receives the same $n-1$ new samples as the first $n-1$ individual whitening filters, plus one additional new sample, further comprising a delay line comprised of a plurality of serially coupled delay line elements each having a delay of one symbol interval, said delay line having an input coupled to an output of said signal connection matrix and providing the $N_s N_{rx}$ parallel whitening filters $\mathbf{w}_{j,k}$ with delayed versions of said signal samples, said whitening filter comprising N_{rx} outputs for outputting whitened filtered signal samples to said multi-antenna RAKE receiver.

16. A CDMA mobile station as in claim 15, where said whitening filter and said multi-antenna RAKE receiver together comprise a linear (minimum mean-square error) channel equalizer.

17. A CDMA mobile station as in claim 15, where said whitening filter and said multi-antenna RAKE receiver together comprise a multi-antenna space-time equalizer that optimally performs beam-forming while suppressing inter-cell interference.
18. A CDMA mobile station as in claim 15, where said same whitening filter is used for receiving transmissions from a plurality of base stations during a soft handoff procedure.